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FIBER REINFORCEMENT FOR RAPID STABILIZATION OF SOFT CLAY SOILS

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14. ABSTRACT

Since World War II, the military has sought methods for rapid stabilization of weak soils for support of its missions worldwide. Over the past 60 years, cement and lime have been the most effective stabilizers for road and airfield applications, although recent developments show promise from nontraditional stabilizers, such as reinforcing fibers. The benefits derived from fibers may depend on whether they are used alone or in combination with chemical stabilizers. The purpose of the research described in this paper is to investigate the ability of stabilizers to increase the strength of two soft clay soils within 72 hours to support C-17 and C-130 aircraft traffic on contingency airfields. Laboratory test results showed that longer fibers increased the strength and toughness the most for a clay treated only with fibers. For a clay treated with fibers in addition to a chemical stabilizer, shorter fibers increased toughness the most, but the fibers had little effect on strength. Higher dosage rates of fibers had increasing effectiveness, but mixing became difficult for fiber contents above 1%. Poly(vinyl) alcohol (PVA) fibers were anticipated to perform better than other inert fibers due to hydrogen bonding between the fibers and clay minerals, but these fibers performed similar to other fibers.

15. SUBJECT TERMS
Soil, Stabilization, Contingency, Airfield, C-17, C-130, Portland Cement, Lime, Geo-synthetic Fibers and Calcium Carbide, Clay, subbase, base, polymer, super plasticizer, accelerator, roadminer, quicklime and J.H. Becker Co.

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INTRODUCTION

Since World War II, the military has had need for stabilizing weak soils to support overseas operations, and as a result, initiated research programs on rapid soil stabilization. The goal was to find a stabilizer that could be quickly and easily mixed into weak soil to create a pavement that could support traffic from military aircraft. Over the past 60 years, progress has been made, but a "magic juice" has not yet been found that has the ability to convert a weak soil to a strong material with very little effort and in a matter of hours. Cement and lime are still among the most effective stabilizers in use today, although mapy claims have been made for nontraditional stabilizers, such as reinforcing fibers. The benefits derived from fibers may depend on whether they are used alone or in combination with chemical stabilizers, such as cement and lime.

The purpose of this research is to determine the most effective stabilizer to increase the strength of wet and soft clay soils within 72 hours for contingency airfields. The Air Force Research Laboratory (AFRL) requested that the soft clay soils have an initial California Bearing Ratio (CBR) of 2, which represents a very poor subgrade condition. After treatment, the stabilized soil must sustain aircraft traffic from Globemaster C-17s and Hercules C-130s. For added strength, the stabilized soil may be covered with a light-weight prefabricated aluminum grid or crushed aggregate, depending on availability.

The study that is discussed in this paper is part of comprehensive project using unconfined compression strength (UCS) tests to screen and compare the effectiveness of different stabilizers at a constant dosage rate of 5% by dry weight of soil. This dosage rate was selected because this is within a typical and reasonable range used in the field for soil stabilization. Once the most effective stabilizers are determined, the clay will be treated with various dosage rates of stabilizers and evaluated with both UCS and CBR tests in a follow-up study. Details of the complete project are discussed and summarized elsewhere (*1*). A similar study, currently being performed by the U. S. Army Corps of Engineers at the Engineering Research and Development Center, is focusing on soil stabilization of silty sand and clay (*2, 3*) for unsurfaced airfields (*4, 5*) as part of the Joint Rapid Airfield Construction program (*6*).

This paper reviews a number of different fiber types and their potential for stabilizing soft clay soil. The results of UCS tests performed on two clays treated with fibers and chemical stabilizers are presented and discussed.

LITERATURE REVIEW

Polypropylene Fibers (FP Fibers)

Polypropylene is a common material used for fiber reinforcement of soils, and it is manufactured in two forms: monofilament and fibrillated. Monofilament fibers are individual, cylindrical fibers. Fibrillated fibers are flat, tape-like fibers that can be described as a latticework of "stems and webs" as the fibers break apart during mixing and compaction (*7*).

Nylon Fibers

Nylon fibers are used as reinforcement in concrete to increase its ductility, durability, and toughness. When nylon fibers are used in concrete, they can absorb water, allowing the fibers to cure the concrete from the inside out (*8*). This absorbed water also contributes to adhesion between the fibers and concrete. Although scant research has been done on the use of nylon

fibers with soil, these fibers may mechanically and chemically stabilize soil, especially when combined with cement.

Poly(vinyl) Alcohol (PVA) Fibers

PVA fibers are typically not used for soil stabilization, but they are used as reinforcement in concrete to increase ductility, durability, and toughness because hydrogen bonds form between the hydroxyl groups of the PVA fibers and cement particles (*9*). However, clay has been stabilized with PVA solution instead of PVA fibers, where hydrogen bonds have also formed between the hydroxyl groups of the PVA molecules and the silicate sheets of the clay (*10*). Combining these two findings, the hydroxyl groups of the PVA fibers should theoretically form hydrogen bonds with the silicate sheets of the clay and could be effective stabilizing the clay soil both chemically and mechanically. If the soil is also treated with cement in addition to PVA fibers, the fibers may bond better to a clay-cement mixture than clay alone, since bonding between fibers and cement has been verified.

Occasionally, the hydrogen bonding between the PVA fibers and concrete is so strong that the PVA fibers rupture instead of pulling out of the cement matrix (*9*). If the PVA fibers do rupture, this fiber reinforced concrete may be too brittle for a particular application. To counteract this phenomenon, some PVA fibers are coated with an oiling agent so that the PVA fibers will pull out of the cement matrix instead of rupturing.

Portland Cement and Lime

Portland cement and lime have long been used for soil stabilization, and their chemistry and effects in soil have been well described in the literature (*11-14*).

Calcium Carbide

Calcium carbide is used for the Speedy Moisture Test (ASTM D 4944 (*15*)), but apparently has not been used for soil stabilization. However, calcium carbide should stabilize soil in a manner similar to lime and could actually be more effective than lime.

When calcium carbide reacts with water in the soil, the end products are acetylene gas and hydrated lime, with production of quicklime during an intermediate step. More water is consumed in these chemical reactions than quicklime hydration alone. In addition, more heat is generated by the calcium carbide reactions, which would evaporate more water than would be evaporated by quicklime hydration alone. Furthermore, if the acetylene gas were captured and combusted, even more water could be driven off.

MATERIALS AND METHODS

The following sections describe index properties of the two clays, test procedures used to determine the UCS of the soil-stabilizer mixtures, and properties of the stabilizers.

In this study, stabilizers were categorized as primary or secondary stabilizers. The primary stabilizers were applied at a dosage rate of 5% chemical stabilizer or 0.05% to 1% fibers by dry weight of soil. As secondary stabilizers, fibers were used in addition to primary chemical stabilizers. All of the fibers used as secondary stabilizers were applied at a dosage rate of 1% by dry weight of soil.

Testing Program

Soil Characterization

ASTM standards were used to determine the classification, Atterberg limits, particle size distribution, specific gravity, and organic content of two clays, which are known as Staunton clay and Vicksburg Buckshot clay (VBC). Mineralogical analyses were also performed.

Initial Water Contents

Water contents of both soils were adjusted to produce the same initial untreated strength, as represented by an initial CBR of about 2, which was selected by the ARFL because this represents a very poor subgrade condition. CBR values were determined for both soils according to ASTM D 1883 (*15*) at various water contents using standard Proctor effort (ASTM D 698 (*15*)). Once a well-defined curve of CBR vs. water content was established, the required water content for a CBR of 2 could be determined. The required initial water contents for the Staunton clay and VBC to achieve a CBR of 2 were determined to be 33.5% and 44.2%, respectively.

Sample Preparation and Testing

For uniformity, the unprocessed soil was first air dried, broken down to particle sizes that could pass a #4 sieve, and then hydrated to the appropriate water content. The appropriate amount of stabilizer was added according to the desired percentage by dry weight of soil necessary for each batch. Kitchen stand mixers were used to mix the stabilizers into the clay for a mixing time of five to ten minutes. When fibers were used, some fibers tended to cluster and "bunch up" during mixing, but the majority of the fibers did not segregate from the wet clays used in this research. More difficulties with mixing and segregation may occur in drier soils.

The soil was then compacted into four plastic tubes having an internal diameter of 2 inches (50 mm) and height of 4 inches (100 mm). To compact the samples, a machined aluminum stand was used to hold the mold in place and a small drop hammer was used for compaction (*16*). The soil was placed in 5 lifts, and each lift was compacted to produce the same density as produced by ASTM D 698 (*15*) at the same water content.

After compaction, both ends of the sample were leveled using a metal screed, capped with a plastic lid, and sealed using electrical tape. The samples for each batch were then stored in a humid room for curing times of 1, 3, 7, and 28 days, after which the samples were removed and carefully extruded from the molds. UCS tests were run according to ASTM D 2166 (*15*) at a strain rate of 1% per minute.

Two batches were prepared and tested to determine the three-day UCS for each stabilizer or combination of stabilizers. The UCS was plotted against curing time for both batches, and the three-day UCS was calculated from a trend line that best fit the data. This process mitigates the effect of scatter in the data.

Stabilizers

Polypropylene Fibers

Two types of polypropylene fibers were used. The fibrillated polypropylene (FP) fibers are flat fibrillated fibers that are 0.001 inches (0.025 mm) thick, variable in width, and 0.75 inches (19 mm) long, with a specific gravity of 0.91. The FP fibers have a tensile strength of 97 ksi (0.67 GPa) and a Young's Modulus of 580 ksi (4 GPa). The monofilament polypropylene (MP) fibers

are 0.75 inches (19 mm) long and have a nominal diameter of 0.002 inches (0.051 mm). The MP fibers have a specific gravity of 0.92 and a Young's Modulus of 550 ksi (3.8 GPa).

Nylon Fibers

The nylon fibers are 0.75 inches (19 mm) long and 0.0013 inches (0.033 mm) in diameter, with a specific gravity of 1.16. These fibers have a tensile strength of 130 ksi (0.9 GPa) and a Young's Modulus of 750 ksi (5.2 GPa). The nylon fibers can absorb up to 4.5% of their weight in water.

PVA Fibers

Two types of PVA fibers were used. The PVA1 fibers are 0.33 inches (8.4 mm) long and 0.0016 inches (0.041 mm) in diameter, with a specific gravity of 1.3. The PVA1 fibers have a tensile strength of 203 ksi (1.4 GPa). The PVA2 fibers are 0.50 inches (13 mm) long and 0.004 inches (0.1 mm) in diameter, with a specific gravity of 1.3. The PVA2 fibers have a tensile strength of 160 ksi (1.1 GPa) and a Young's Modulus of 4210 ksi (29 GPa). Both fibers are resin bundled for easier mixing. According to the distributor, the PVA2 fibers are coated in an oiling agent, while the PVA1 fibers are not.

Portland Cement

Both Type I/II and Type III cement were used. ASTM C 150 (*17*) specifies that the composition of both Type I and Type III cement has a maximum of 55-56% C_3S, 19% C_2S, 10% C_3A, and 7% C_4AF, while the composition of Type II cement has a maximum of 51% C_3S, 24% C_2S, 6% C_3A, and 11% C_4AF. Type I/II cement must meet both of the compositional requirements for Type I and Type II cements (*18*).

Lime

Pelletized and pulverized quicklimes were used. The pelletized quicklime contains more than 90% CaO and has particles less than 0.125 inches (3.2 mm) in size. The pulverized quicklime contains more than 90% CaO and has particles less than 0.0058 inches (0.15 mm) in size.

Calcium Carbide

The calcium carbide used in this study contains 75-85% calcium carbide and 10-20% calcium oxide.

RESULTS

Soil Characterization

For the mineralogical analyses, the quantity of kaolinite in each clay fraction was first determined by thermogravimetric analysis (TGA) using Georgia kaolinite as a standard (Dr. Lucian Zelazny, unpublished data). The remaining percentages of minerals were then determined by X-ray diffraction using the TGA-determined kaolinite as an internal standard. Based on these analyses, the clay fraction consists of 45% kaolinite, 20% montmorillonite, 10% mica, 10% vermiculite, 4% hydroxyl interlayered vermiculite, 1% gibbsite, and 10% quartz for the Staunton clay, and 10% kaolinite, 60% montmorillonite, 10% mica, 15% vermiculite, and 5% quartz for the VBC. The percentage of kaolinite, gibbsite, and quartz may have an error margin of about 2-3%, and the remaining minerals may have an error margin up to 5%. Although

amorphous material was not detected, up to 2-3% may be present. The index properties of the clays are shown in Table 1. Even though both clays are classified as highly plastic, they have quite different compositions and properties.

TABLE 1 Summary of Soil Index Properties

Soil Name	USCS	Group Name	Atterberg Limits			Fines (<#200) (%)	Max. Dry Unit Weight[a] (pcf)[b]	Opt. Moisture Content[a] (%)	Specific Gravity
			LL	PL	PI				
Staunton Clay	CH	Fat Clay	53	25	28	81	92.0	26.0	2.74
VBC	CH	Fat Clay	84	35	49	> 95	89.8	27.8	2.79

[a] **Standard Compactive Effort (ASTM D 698)**
[b] **1 pcf = 0.1571 kN/m^3**

Unconfined Compressive Strength Tests

Staunton Clay

Fibers as Primary Stabilizers Figure 1 shows the three-day normalized UCS values for Staunton clay treated with the indicated fiber types and dosages. The normalization is by the untreated Staunton clay's three-day UCS of 16 psi (110 kPa).

In addition to increasing strength, fibers are known for increasing toughness, which is the amount of energy a material can absorb. Toughness is important because chemically treated-soils without fibers exhibit brittle stress-strain curves and have relatively little toughness, which may cause the treated soil to crack and fail suddenly. Not only will a runway fail more quickly, but this sudden cracking and failure can also create foreign object debris on a runway surface, which fibers have been found to reduce (*2*). An increase in normalized toughness is desirable, as the longevity of the airfield would be expected to increase with increasing toughness.

Toughness can be evaluated by calculating the area underneath the stress-strain curve. Figure 2 shows the three-day normalized toughness calculated at 15% strain for Staunton clay treated with the same fiber types and dosages as in Figure 1. The normalization in Figure 2 is by the three-day toughness of 2.0 in-lb/in^3 (13.8 kJ/m^3) for the untreated Staunton clay. For both untreated and treated Staunton clay, the UCS did not increase with curing time, and failure occurred at high strains around 10% and greater.
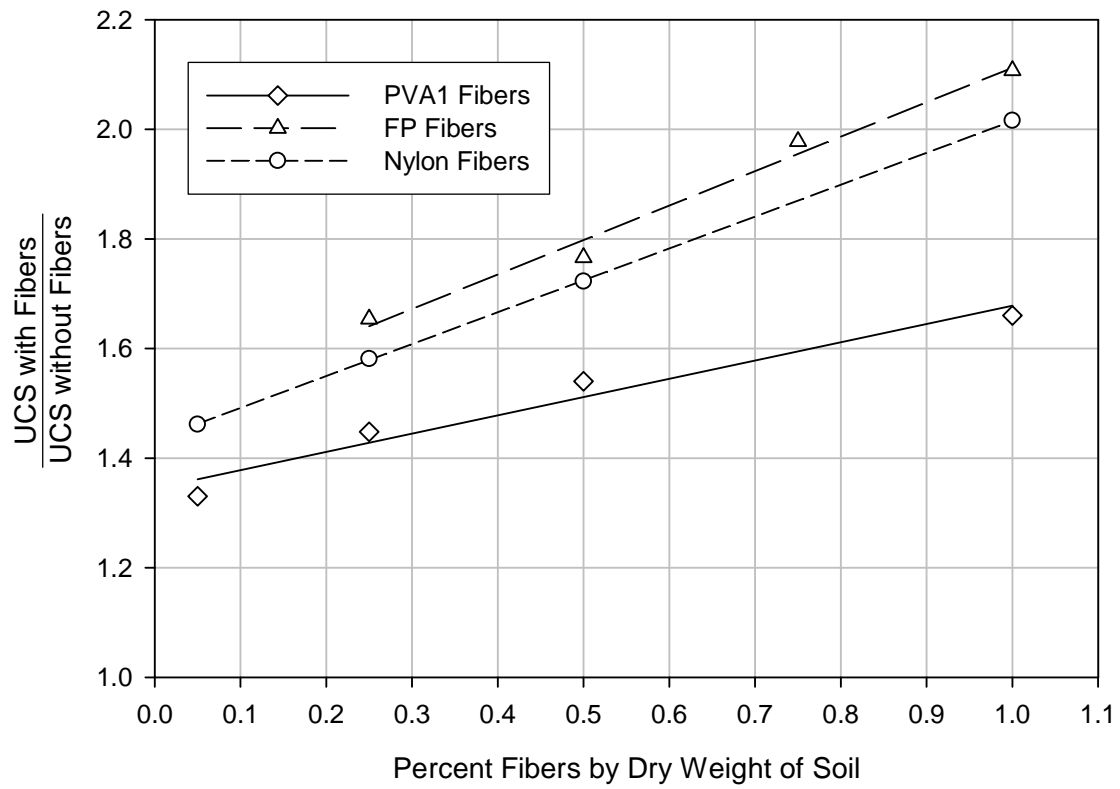
FIGURE 1 Three-day normalized UCS vs. percent fibers by dry weight of Staunton clay.
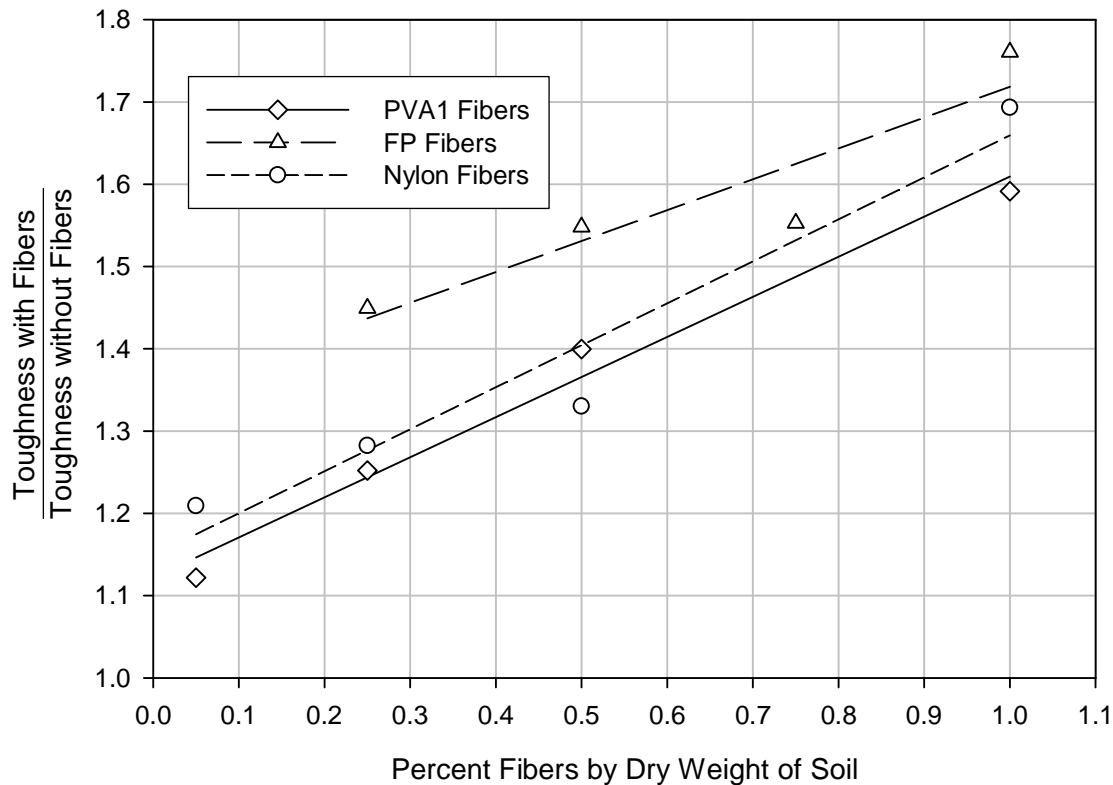
FIGURE 2 Three-day normalized toughness calculated at 15% strain vs. percent fibers by dry weight of Staunton clay.

Figures 1 and 2 show that the FP fibers increased strength and toughness the most, followed by the nylon fibers, and then the PVA1 fibers. Based on these results, the longer FP and nylon fibers consistently performed better than the shorter PVA1 fibers. Although strength and toughness increased with increasing fiber content, the maximum dosage rate was limited to 1% of dry weight of soil because mixing became difficult at greater dosage rates.

Fibers as Secondary Stabilizers Table 2 shows the three-day UCS for Staunton clay treated with 5% primary stabilizer without fibers and with 1% fibers by dry weight of soil. In general, the addition of fibers decreased the maximum strength gain of the cement-treated clay, and more decrease occurred with longer fibers. This is shown in Figure 3, where the three-day UCS values with fibers are normalized by the three-day UCS values without fibers. The 0.33-in.-long PVA1 fibers had little effect on the strength of the cement-treated clay, the 0.5-in.-long PVA2 fibers reduced the strength slightly, the 0.75-in.-long FP fibers reduced the strength more, and the 0.75-in.-long nylon fibers reduced the strength the most. The effect of fiber diameter on normalized strength was also evaluated, but the results were inconsistent, possibly due to simultaneous variations in other factors that may have had a greater influence on strength, such as fiber shape and length.

**TABLE 2 Three-Day UCS for Staunton Clay Treated with 5%
Primary Stabilizer and 1% Fibers by Dry Weight of Soil**

Fiber Type	UC Strength			
	No Primary Stabilizer (psi)[a]	Type I/II Cement (psi)	Type III Cement (psi)	Calcium Carbide (psi)
No Fibers	16	284	266	129
PVA1 Fibers	26	258	275	148
PVA2 Fibers	—[b]	240	235	—
FP Fibers	33	205	212	—
Nylon Fibers	31	174	190	157

[a] **1 psi = 6.89 kPa**
[b] **Tests not conducted**

**FIGURE 3 Three-day normalized USC vs. fiber length for Staunton clay treated with 5%
primary stabilizer and 1% fibers by dry weight of soil. (1 inch = 25.4 mm)**

Table 2 and Figure 3 also show that the addition of fibers to calcium carbide-treated Staunton clay increased the maximum strength of the mixture compared to treating Staunton clay with calcium carbide alone, which is the opposite effect that fibers had on cement-treated Staunton clay. However, when nylon fibers were added to calcium carbide-treated Staunton clay, the maximum strength occurred at high strains near 15%, which was unlike the cement- and

fiber-treated Staunton clay specimens, which reached their maximum strength at around 1% strain.

For reference, Figure 3 also shows that fiber treatment increased the strength of the Staunton clay without chemical stabilizers. In this case again, the maximum strength occurred at strains greater than 10%.

The addition of fibers tended to increase the toughness of the Staunton clay treated with 5% primary stabilizer. Table 3 shows the three-day toughness values for the Staunton clay treated with 5% primary stabilizer without fibers and with 1% fibers by dry weight of soil. In this case, the toughness is calculated at 2% strain. Figure 4 shows the effect of fiber length on the three-day normalized toughness, where the normalization is by the three-day toughness for each primary stabilizer without fibers. The Staunton clay treated with 5% primary stabilizer and 1% of the shorter fibers produced the highest toughness values.

TABLE 3 Three-Day Toughness Calculated at 2% Strain for Staunton Clay Treated with 5% Primary Stabilizer and 1% Fibers by Dry Weight of Soil

	Toughness			
Fiber Type	No Primary Stabilizer (in-lb/in^3)[a]	Type I/II Cement (in-lb/in^3)	Type III Cement (in-lb/in^3)	Calcium Carbide (in-lb/in^3)
No Fibers	0.104	2.8	3.1	1.85
PVA1 Fibers	0.151	4.2	4.7	2.3
PVA2 Fibers	–[b]	3.5	3.6	–
FP Fibers	0.169	3.4	3.3	–
Nylon Fibers	0.152	3.0	2.5	1.86

[a] 1 in-lb/in^3 = 6.89 kJ/m^3
[b] Tests not conducted

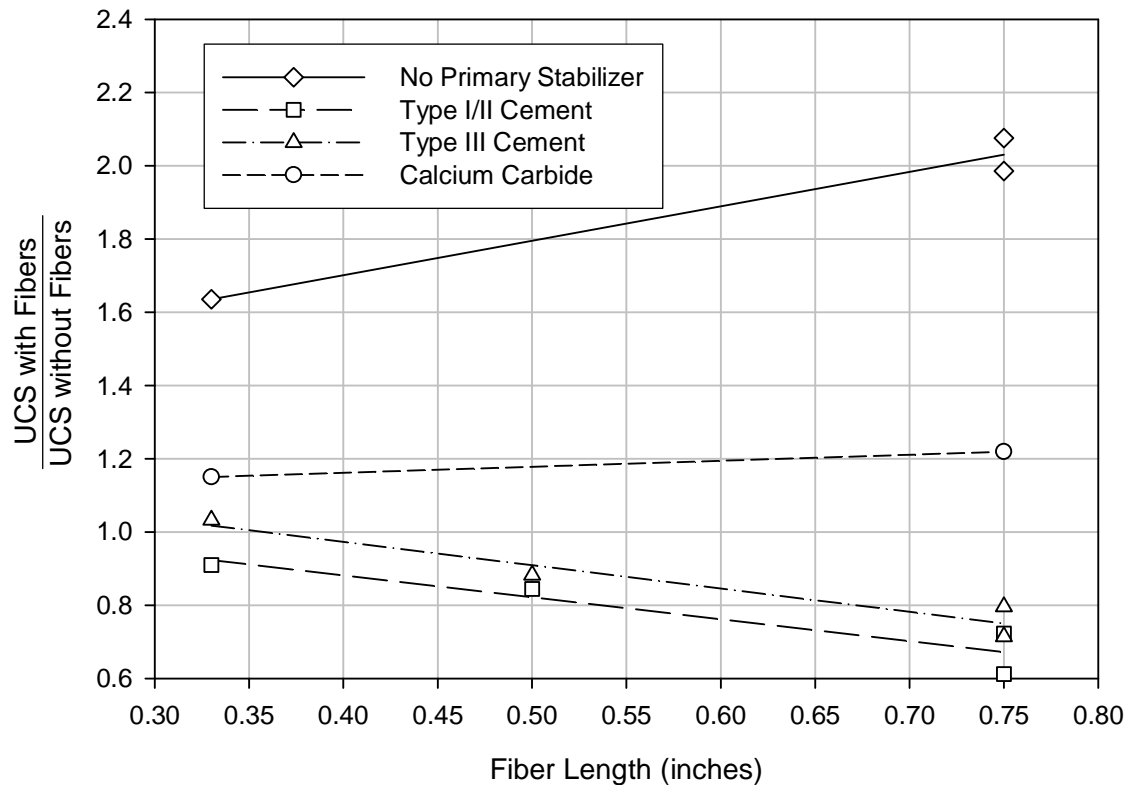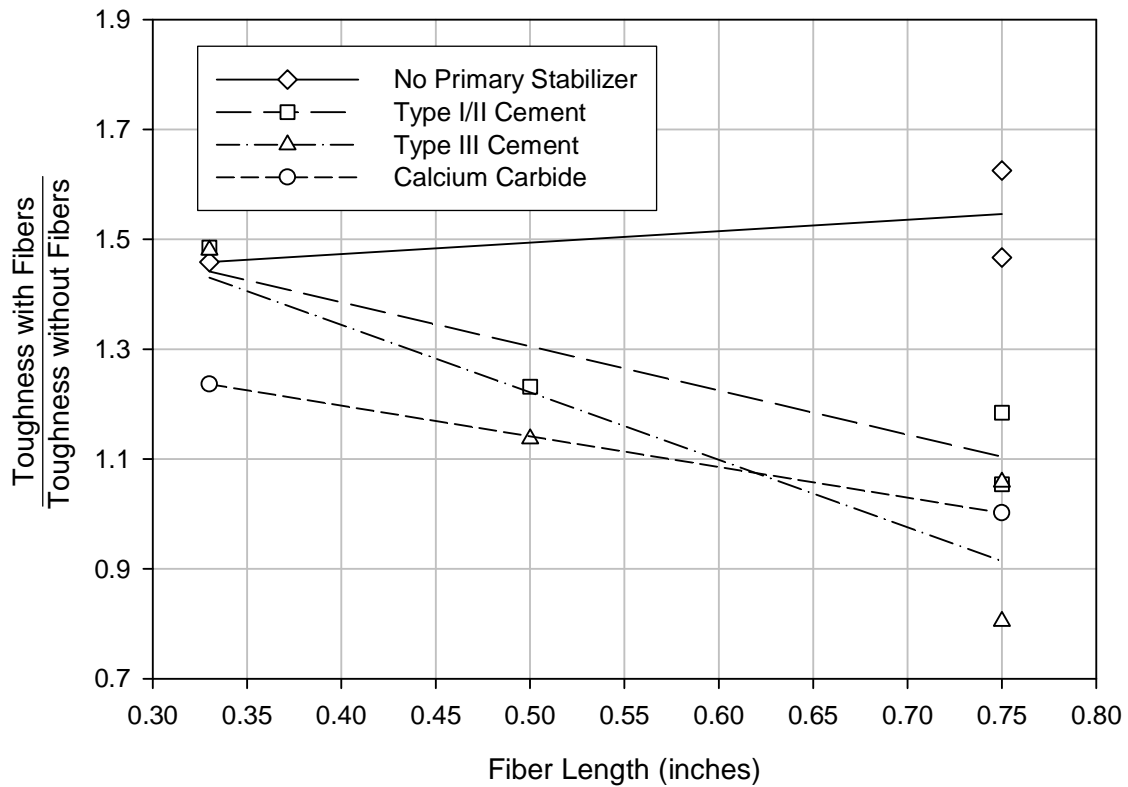**FIGURE 4 Three-day normalized toughness calculated at 2% strain vs. fiber length for Staunton clay treated with 5% primary stabilizer and 1% fibers by dry weight of soil. (1 inch = 25.4 mm)**

Figure 5 shows the three-day stress-strain curves for Staunton clay treated with 5% Type III cement and 1% fibers by dry weight of clay. The stress-strain curves illustrate the changes in toughness and strength for each fiber type. Only the PVA1 fibers increased toughness without decreasing strength.

FIGURE 5 Three-day stress-strain curves for Staunton clay treated with 5% Type III cement and 1% fibers by dry weight of soil. (1 psi = 6.89 kPa)

Vicksburg Buckshot Clay

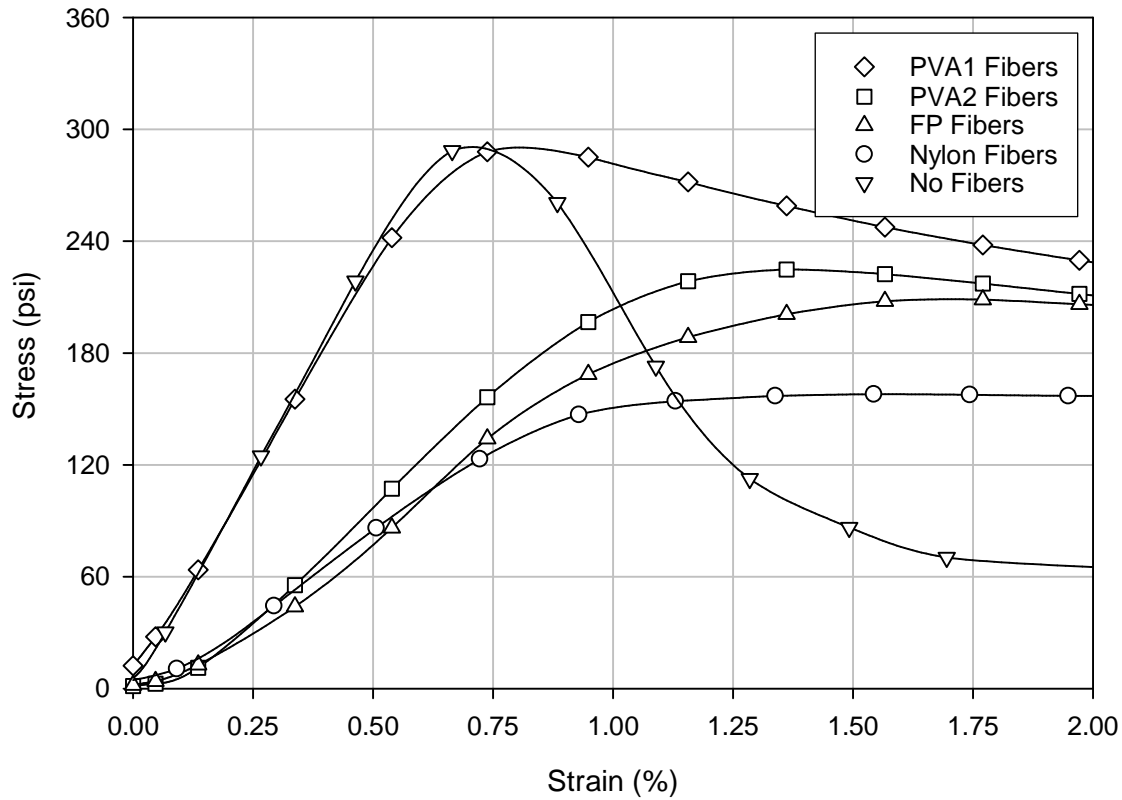**Fibers as Secondary Stabilizers** In an attempt to isolate the contribution of chemical bonding between the PVA1 fibers and soil, the nylon and MP fibers were cut in half, resulting in a length of 0.375 inches (9.5 mm) to approximate the length of the PVA1 fibers, which have a length of 0.33 inches (8.4 mm). Therefore, the chemical interactions should largely be responsible for differences between the fiber-reinforced soil specimens, since the nylon, MP, and PVA1 fibers have similar diameters of 0.0013 inches (0.033 mm), 0.002 inches (0.051 mm), and 0.0016 inches (0.041 mm), respectively.

Table 4 shows the three-day UCS for VBC treated with 5% primary stabilizer without fibers and with 1% fibers by dry weight of soil. The addition of 1% halved MP fibers or PVA1 fibers to VBC treated with either 5% pelletized quicklime, pulverized quicklime, or calcium carbide all produced slightly higher strengths than exhibited by the chemically stabilized VBC without fibers. In contrast, the VBC treated with 5% Type III cement experienced very little change in strength due to the addition of fibers. Without treatment, the VBC had a three-day UCS of 7 psi (48 kPa) and did not appear to gain strength over time.

TABLE 4 Three-Day UCS for VBC Treated with 5% Primary Stabilizer and 1% Fibers by Dry Weight of Soil

	UC Strength				
Fiber Type	No Primary Stabilizer (psi)[a]	Type III Cement (psi)	Pelletized Quicklime (psi)	Pulverized Quicklime (psi)	Calcium Carbide (psi)
No Fibers	7	112	93	79	89
PVA1 Fibers	—[b]	108	103	105	99
Halved MP Fibers	—	110	98	—	99
Halved Nylon Fibers	—	109	—	—	—

[a] 1 psi = 6.89 kPa
[b] Tests not conducted

Figure 6 shows the three-day stress-strain curve for VBC treated with 5% Type III cement and 1% fibers by dry weight of soil. The shapes of the stress-strain curves for the VBC treated with cement and fibers were much more similar than the corresponding plots for Staunton clay (Figure 5). These results indicate that the fiber dimensions, not the chemical compositions of the fibers, influence the stress-strain response of the cured mixture.
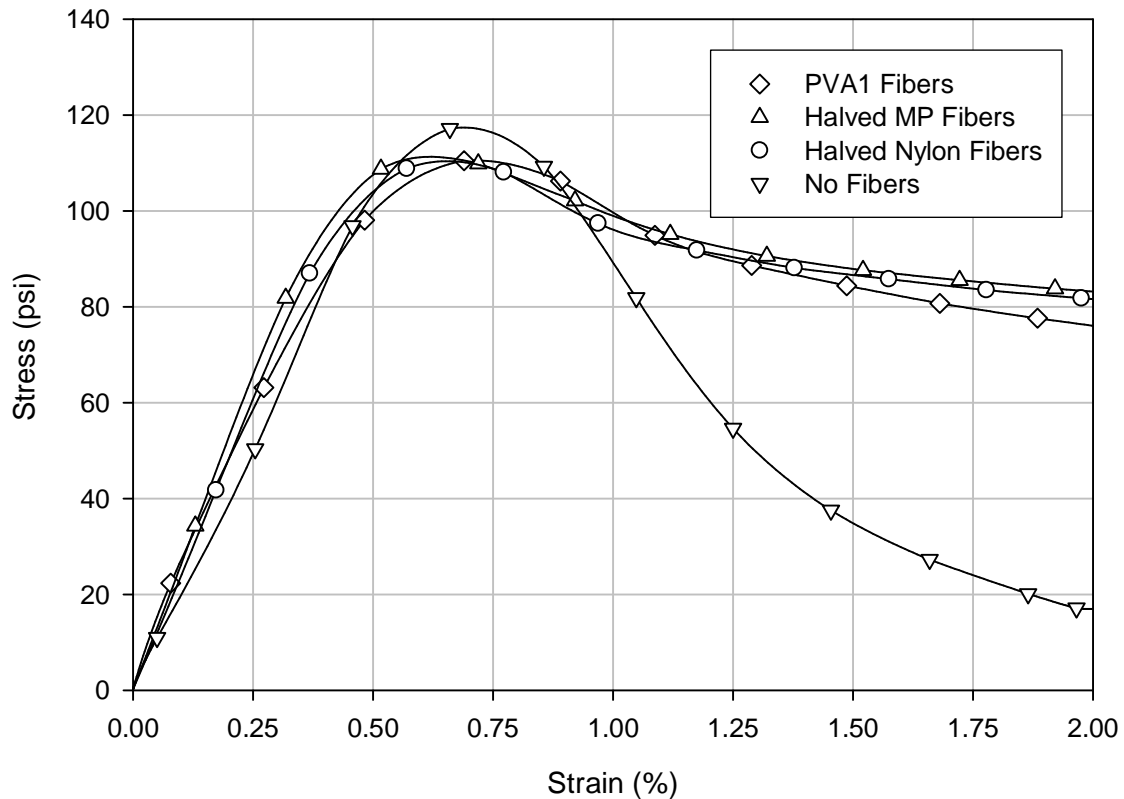

FIGURE 6 Three-day stress-strain curves for VBC treated with 5% Type III cement and 1% fibers by dry weight of soil. (1 psi = 6.89 kPa)

DISCUSSION OF RESULTS

Fibers as Primary Stabilizers

When used as primary stabilizers, all of the fiber types and dosages increased the strength and toughness of the Staunton clay. Overall, treatment with the longer FP fibers at the highest mixable dosage rate of 1% increased the strength and toughness of the Staunton clay the most. Longer fibers may have been more effective in this case because the untreated soil was quite ductile and failed at high strains, which may have allowed a greater portion of the tensile strength of the longer fibers to be mobilized.

The strength increase from the addition of fibers as a primary stabilizer may be more significant than the increase in toughness, since the untreated Staunton clay with a water content of 33.5% is already quite ductile. However, even the best UCS results for the wet Staunton clay treated with fibers were still very low. Therefore, using fibers as a primary stabilizer for clays with high water contents may not provide enough improvement to be of any significant value in most field applications.

Fibers as Secondary Stabilizers

For a secondary stabilizer to be considered effective, the secondary stabilizer must improve performance more than the primary stabilizers at a lower dosage rate, with this improvement being great enough to outweigh the added cost and complexity.

As secondary stabilizers, most of the fiber types increased the toughness of the chemically treated Staunton clay and VBC, but often decreased the UCS. Shorter fibers tended to increase toughness the most and decrease UCS the least for Staunton clay treated with 5% primary stabilizer and 1% fibers. Shorter fibers may have been more effective because there are a larger number of shorter fibers than longer fibers at the same dosage rate, so more fibers may be properly oriented and positioned to resist loading. However, longer fibers were better for the Staunton clay treated with 5% calcium carbide and 1% nylon fibers. Similar to the untreated Staunton clay, this mixture reached its peak strength at high strains where the fibers may become more effective as they become more straightened and tensioned. If the toughness effects of fiber reinforcement are mainly influenced by fiber length and soil stiffness, shorter fibers may be more effective for untreated clays with much lower water contents than the clays tested in this study, since such clays would have more stiff and brittle responses.

The decrease in UCS with the addition of 1% fibers to the Staunton clay treated with 5% primary stabilizer may have been caused by planes or pockets of weakness introduced by the fibers. Either the fibers may have been poorly distributed throughout the soil, or the load may not be transferred well between the fibers and a soil with such a high water content, since the water may have acted as a lubricant (*19*). The PVA2 fibers may have introduced larger pockets of weakness as a result of the larger fiber diameter, which is more than two times the diameter of any of the other fibers. In addition, the oiling agent covering the fibers may have acted as an additional lubricant between the fibers and the soil. The FP fibers may have introduced small failure planes, since these may not have been mixed well into the soil and did not fully break apart into "stems and webs" (*7*). The nylon fibers may have also introduced pockets of weakness because these fibers also did not mix well into the soil and often "bunched up," creating pockets of nylon fibers throughout the soil.

The fiber composition did not have a large influence on effectiveness, as shown by the similar stress-strain curves for VBC treated with 5% Type III cement and 1% fibers of different

materials but all of approximately the same dimensions. In addition, the fibers were also observed to pull out of the soil matrix and no distress of the fibers was visible, so the fiber material strength most likely could not influence the treated soil's strength.

The PVA fibers did not exhibit any evidence of improvement due to hydrogen bonding with untreated or treated clay. In treating the Staunton clay and VBC, the PVA fibers showed no signs of distress after failure, and in treating the VBC, the fibers performed similarly to the MP and nylon fibers, which had approximately the same dimensions. Although Kanda and Li (*9*) state that the effectiveness of the PVA fibers is independent of water-to-cement ratio (*wc/c*) for concrete mixtures, the effectiveness of the PVA fibers may have been influenced by the drastically higher *wc/c* of the Staunton clay and the VBC, which was about 8 to 22 times higher than the *wc/c* of a typical concrete mixture.

CONCLUSIONS

The combination of chemical stabilizer and short fibers was most effective in treating the two clays, since the chemical stabilizer greatly increased the UCS and the short fibers significantly increased the toughness. Because soil treated with only a chemical stabilizer is often brittle, the addition of the short fibers may be important. Other key findings are listed below.

1. When used as primary stabilizers, increasing the dosage rate of fibers continued to increase the strength and toughness of the soil, but the maximum dosage rate was limited to 1% of the dry weight of soil because mixing became difficult above this dosage.
2. When used as primary stabilizers, longer fibers may have increased the strength more than shorter fibers because the soil was ductile and bulged at high strains before failure, which should have allowed a greater mobilization of the strength of long fibers before pullout.
3. Although adding fibers as a primary stabilizer to a soft clay may have resulted in strength increases, the magnitude of the increase may not be enough for airfield applications.
4. The most important effect of adding fibers to a clay treated with a primary chemical stabilizer may have been an increase in toughness, since soil treated with only a primary stabilizer was often brittle and the fibers had little effect on peak strength.
5. As secondary stabilizers, shorter fibers appeared to increase toughness the most, since the treated soil was brittle and failed at small strains, where a greater number of short fibers may have been oriented to resist loading than fewer long fibers at the same dosage rate.
6. As secondary stabilizers, the size and shape of the fibers may have been very important, since fibers that were too large or did not disperse well during mixing may have decreased the UCS of a treated clay by introducing failure planes or pockets of weakness.
7. The fiber material may not have had much influence on the UCS as secondary stabilizers, as demonstrated by the similar stress-strain curves of soil treated with different fiber types of similar dimensions.
8. Hydrogen bonding between the PVA fibers and untreated or treated clay may not have occurred as a result of the very high *wc/c* of the Staunton clay and VBC.

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